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MULTI-WAVEBAND OBSERVATIONS OF COLLIDING GALAXIES

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1. Introduction

Colliding galaxies represent a major challenge to both theorists and observers because of the large variety of phenomina which are expected to come into play during the interaction. Strong gravitational fluctuations may drive non-linear waves and instabilities throughout the stars and gas leading to enhanced star formation, nuclear activity and ultimately a mixing of the morphological components of the original galaxies. One relatively uncomplicated class of colliding galaxy where stellar waves play an important role in star formation are "ring" galaxies. Ring galaxies are probably formed when a companion galaxy passes through the centre of a disk system driving circular waves through the disk (Lynds and Toomre 1976,Toomre 1978, Struck-Marcell 1990). Off-centre collisions can generate non-circular waves and can be loosely described as banana-shaped although they may exhibit more complex forms as the waves expand into the disk (See also Struck-Marcell; this volume). The propagation of such stellar and gaseous waves through the disk leads to enhanced star formation (e.g. Appleton and Struck-Marcell 1987a; Jeske 1986) and provides a unique probe of the response of the ISM to a propagating wave (See Appleton and Struck-Marcell 1987b).

2. The Observations

We report here results for 3 systems; the irregular ring Arp143 (=VV117); Wakamatsu's Seyfert ring (A0959-755;see Wakamatsu and Nishida 1987; hereafter HN) and the brighter member of the pair of ring galaxies comprising of AM1358-221. The most complete multi-wavelength data is for Arp143. We will describe optical CCD observations made with the 60" Palomar telescope at BV and r band, near-IR images at J (1.25 microns),H (1.65 microns) and K (2.2 microns) bands from the IRCAM InSb array camera on the 3.8m UKIRT telescope and VLA observations at at 20cm in both the neutral hydrogen line and radio continuum. The observations of Wakamatsu's ring and AM1358 where made only in the near-IR, and a comparison is made with available optical plate material.

3. The Results

Figs. 1a and b show the optical IIIaJ image of Wakamastu's ring (taken from WN) and the K-band near-IR image of the same object.

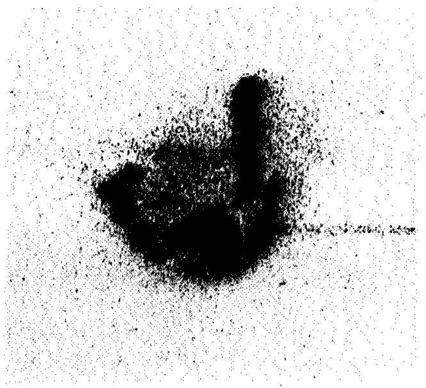


Fig.1a Wakamatsu's Ring: Optical

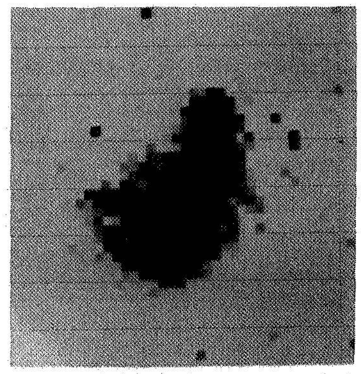


Fig.1b Wakamatsu's Ring: K-Band

In the optical, the galaxy is composed of an irregular ring of bright knots, brighter to the south, which surround the off-centre Seyfert-1 nucleus. To the western-edge a jet-like filament extends out of the ring to the north. This filament is almost certainly the highly distorted companion galaxy which created the ring and is itself now suffering the consequences of dynamical heating. The most prominent K-band emission comes from the ring nucleus and the peculiar companion. However what is remarkable about the near-IR images is the lack of a well-defined ring when compared with sharpness of the optical ring. A diffuse underlying disk is detected clearly with only a hint of an enhancement near the bright optical knots. We will show later that in the regions of the optical knots the near-IR colors are abnormal and are strongly suggestive of thermally heated dust.

The AM1358-221 system is a pair of southern rings which are separated by 5 arcminutes. Figure 2a and b show the optical and K-band images of AM1358-221 respectively. The brighter of the pair (boxed) was imaged through J and K filters at UKIRT. As with Wakamatsu's ring, it is striking that the bright optical ring is very weak when seen in the IR.

The detection of only a weak enhancement of the ring component in the near-IR is perhaps not totally unexpected since the optical light ought to be dominated by young stars. A similar result has been reported by M.Joy (personal communication) in an ongoing study of the Cartwheel ring galaxy. The low surface-density contrast in the light of the old stellar population provides support for the idea that the star-formation is triggered by cloud-cloud collisions due to crowding in the gas wave (See Struck-Marcell and Appleton 1987b) rather than the star formation being a result of gas responding
to the weak stellar potential in the wave. Evidently a rather

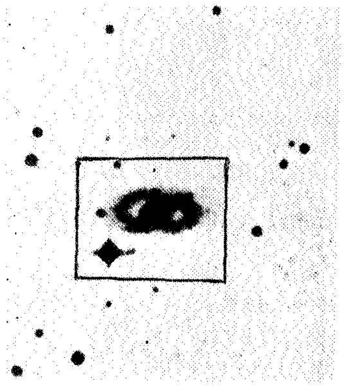


Fig.2a AM1358-221: Optical

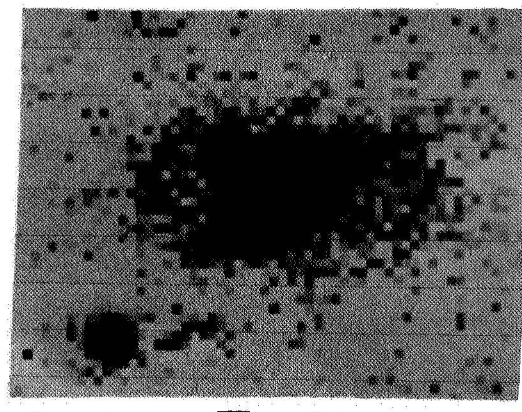
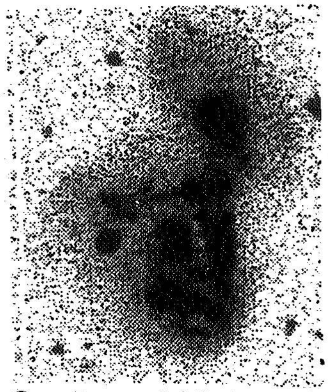


Fig.1b AM1358-221: K-Band

low over-density threshold in the gas wave is suffiecient to drive a strong and vigourous starburst seen in the optical ring.

A consideration of the J-H, H-K colors of Wakamatsu's ring show that all the points measured in the disk, nucleus and companion occupy a region intermediate between the colors of starburst galaxies and QSO's. The nuclei of both galaxies in the Wakamatsu system have IR colors similar to the FIRG (or ELF!) galaxy Arp220. Even the disk component of Wakamatsu's ring has a large H-K color suggesting considerable dust distribution a result perhaps not unexpected given the high total far-IR emission $(L(80) = 1.1\text{x } 10^{11} L_{\odot})$ from the ring noted by WN. One knot in Wakamatsu's ring (marked W1 in Figure 1a) has an extreme H-K color like that of a QSO's and yet is clearly non-nuclear.

In the ramaining part of this paper I will turn my attention to Arp143. This galaxy (shown in Fig. 3a), classified as an irregular ring by de Vaucouleurs de Vaucoulears and Corwin (1976), is obviously not a classical ring but rather a collection of luminous blue knots surrounding the nucleus. The object was first described as a "Nest" (of galaxies) by Verontsov-Velyaminov(1959). HI observations confirm that the blue knots are part of a rotating disk system (NGC2445), and are probably not dynamically separate entities (Appleton et al 1987). The system was also the subject of an early study by Burbidge and Burbidge (1959). The Burbidge's concluded their paper by suggesting that NGC2445 (the more disk-like component of the system) was probably either a galaxy forming in the wake of the elliptical companion NGC2444 or was a galaxy strongly disturbed by a head-on collision with its companion.
The latter view is supported by Appelton et al. who also discovered a huge plume of HI extending away from the system to a distance of 150kpc. A faint optical plume is also detected. We interpret the plume as further evidence that a galaxy has plowed through NGC2445.



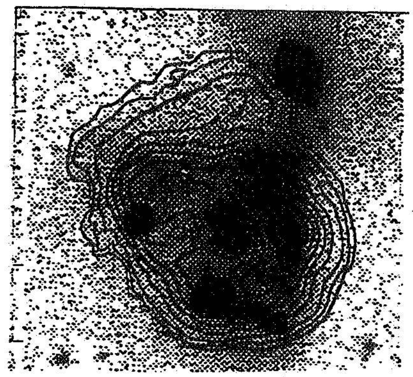
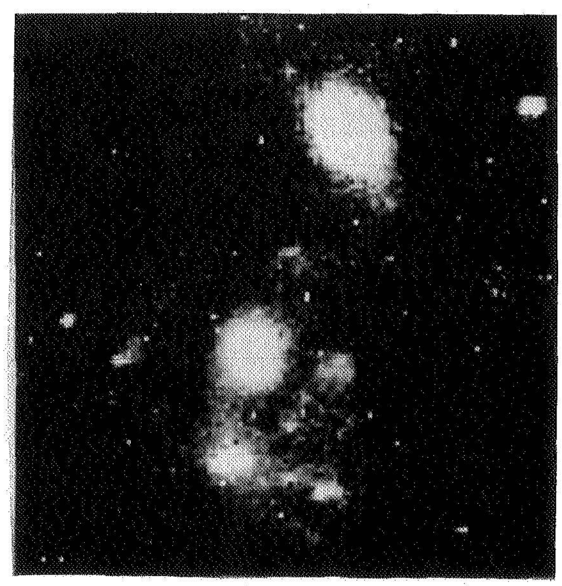


Fig.3a Arp 143=VV117 (V-Band) Fig.3b HI Emission and Optical Knots

The same HI observations also show that the HI disk of NGC2445 has approximately circular outer contours with a strong banana-shaped wave superimposed on its western edge (See Fig.3b). The bright optical knots (shown in Figure 3b) lie on the OUTER-EDGE of the banana-like wave. The morphology of the HI wave is precisely what would be expected from an off-centre collision between a galaxy and a gas-rich disk (See Appleton and Struck-Marcell 1987b). Hence Arp143 would appear to be a ring-galaxy in the process of "turning-on" optically, the optical knots being giant HII regions forming on the leading-edge of the density wave generated in the gas. The optical knots are very blue (B-V ~ 0.4 to 0.6) and show H(alpha) emission (Burbidge and Burbide 1959). If the banana-shaped HI wave is indeed a density wave driven through the gas disk of NGC2445, then a faint stellar wave should also be present in the underlying old stellar disk.

Such a wave might be seen in the K-band light and should be spatially coincident with the HI wave. Figure 3c and d show the



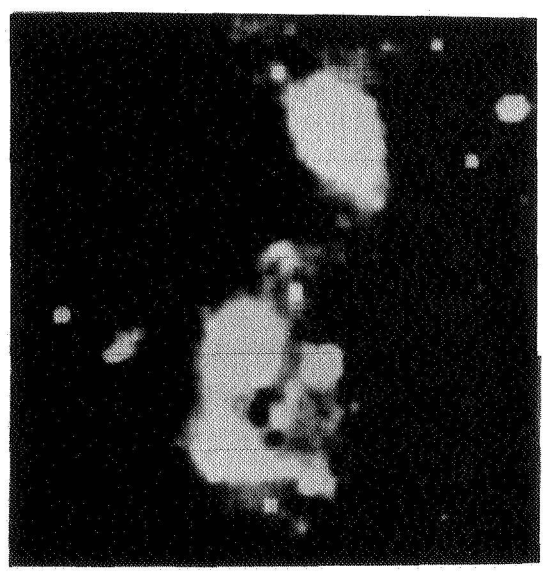


Fig.3c Arp143 (K-Band) Fig.3d Arp143 Smoothed K-band Image

K-band image of Arp143 both before (1.2 arcsec/pix) and after convolving with a 3x3 pix box function. Although very faint optically, a near-IR structure is found which co-incides with the HI wave. This feature is indicated in Fig. 3d and may be part of a large half-ring which encircles the inner disk. The same structure is present much less obvious in the optical images. In contrast, the bright optical knots which lie on the outer edge of the HI wave are very luminous in the K-band image. (One of the knots is probably a late G-type foreground star which was noted by the Burbidges). We note that with the exception of two of the brighter knots, most of the IR emission is consistant with the colors of late-type stars. Power spectra of some selected features obtained by combining the data from the Palomar CCD and the IRCAM photometry clearly show that the emission from the bright knots splits into two separate components, a hot component corresponding to young massive stars and a cooler component. The cooler "bump" in the IR spectrum may either be generated by young supergiants or old disk giants and dwarfs.

This latter ambiguity between old and young stellar populations leads to some problems in the full interpretation of the "knots". If the JH and K emission in the knots is dominated by supergiants (a resonable assumption given the identical spatial position of the IR knots wrt the optical) then the knots are bright "beads" of young stars. On the other hand, the models of Struck-Marcell (1990) predict that caustic "hotspots" can also be produced as stellar disk stars stream through each other. In this case the IR enhancements would be in the old stellar disk, although some star formation would occur as gas piled up at those points. A radio-continuum image of the system (not shown here) shows extended emission associated with the knots lending support to the view that the "chics" in the "Nest" of Arp143 are indeed transient young starforming regions and may well soon be replaced with a fully-fledged ring structure in a few million years from now.

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DISCUSSION

Chatterjee: Is Wakamatsu's ring in the final stage of evolution (like the simulations of Spiegel and Theys)?

Appleton: I do not believe so. Rather I believe it is a young ring. I do not believe that the optical "beads" are a result of the Theys and Spiegel mechanism. Indeed, the "beads" probably do not form from the self-gravity of the ring. The stars propagate through the ring on a timescale which is very short compared with the gravitational free-fall time for the formation of clumps. This is supported by N-body simulations of James and Appleton (1989).

Cutri: I would suggest imaging the galaxies in the 2 μm photospheric CO band. This feature is quite strong in supergiants, but is much weaker in MS stars. Shocked gas, of course, should not exhibit the absorption. Such a measurement might help differentiate between the two cases.

Appleton: I hope you are right! Thank you.